Scaled Physical Modelling of Soil–Vegetation Hydro-Mechanical Interactions

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ABSTRACT: This experimental study investigates the influence of vegetation on the hydro-mechanical behaviour of fine-grained soils, intending to assess how evapotranspiration and suction processes contribute to slope stability. A scaled physical model was constructed using kaolin as the base soil and balsa wood as a root analogue, enabling controlled reproduction of vegetation effects on the soil matrix. The experimental design considered variables such as the number of trees, leaf area, root depth, and wind-exposure duration to identify the most effective configurations for moisture redistribution. Periodic measurements of suction and water content were taken throughout the soil profile, accompanied by comparative analyses to evaluate the role of each variable. The results show that simulated vegetation configuration adopted in this study (balsa wood as a root analogue in kaolin) modifies surface moisture conditions and induces suction gradients that enhance soil strength. While the magnitude of this effect depends on plant type and soil characteristics, the findings demonstrate that, under the controlled conditions tested, vegetation can represent a sustainable and non-invasive strategy for improving slope stability. The study also provides a replicable experimental framework for future research based on scaled physical modelling.

1 INTRODUCTION

Vegetation plays a key role in the stability of natural and engineered slopes by providing mechanical reinforcement through roots and by regulating soil moisture via evapotranspiration, which affects suction and water content (Stokes et al., 2009; Mickovski et al., 2009). In fine-grained soils, vegetation-induced drying can create suction gradients that enhance shear strength and reduce the likelihood of failure (Tarantino & Dainese, 2021). These benefits are particularly relevant for slopes with moderate inclinations, where vegetation mitigates surface erosion, promotes controlled infiltration, and reduces saturation in the upper soil layers—processes that increase apparent friction angle and overall stability (Wu & Watson, 1998; Caicedo & Silva, 2024).

To better understand these mechanisms, this study develops a scaled physical model using kaolin as the base soil and balsa wood as an analogue for roots. The model evaluates how the number of trees, leaf area, root depth, and wind exposure influence moisture redistribution and soil suction. This approach contributes to ongoing efforts to create simplified, yet representative, experimental models of vegetation–soil hydro-mechanical interaction.

Through this controlled system, the study examines the efficiency of simulated vegetation in reducing moisture and mass loss in saturated soils, providing insights that support sustainable slope-stabilisation strategies—particularly in regions exposed to heavy rainfall, erosion, and strong winds.

2 THEORETICAL FRAMEWORK

The interaction between vegetation and soil has been extensively studied due to its significant influence on the stability of natural and reinforced slopes. Plant roots increase soil shear strength through mechanical anchorage and by generating suction in the upper layers (Mickovski et al., 2009). Likewise, evapotranspiration—combining direct soil evaporation with plant transpiration—reduces water content and induces changes in pore pressure that can enhance stability (Tarantino & Dainese, 2021).

The moisture–suction relationship can be described using Soil Water Retention Curves (SWRC), which represent the amount of water the soil can retain in relation to matric suction. In fine-grained soils such as kaolin, these curves often exhibit strong dependence of water content on suction, particularly with pronounced changes at low degrees of saturation.

In this context, the use of analogue materials such as balsa wood makes it possible to replicate root behaviour, both in their capacity to retain and release water. Experimental tests have shown that balsa exhibits physical characteristics that facilitate the simulation of root suction, moisture redistribution, and mechanical interaction with the soil, allowing for controlled analysis of these phenomena. The relationship between water content and suction can be modelled through SWRCs, which are strongly tied to soil porosity and microstructure. In fine soils like the kaolin used in this study, micropores dominate water retention, resulting in high suction values at low moisture levels. The presence of vegetation accelerates changes along this curve by generating zones of differential drying around the roots.

2.1 Hydrological Interaction Between Vegetation and Soil

Vegetation not only reinforces the soil mechanically through its root network but also modifies its hydraulic behaviour through evapotranspiration. This process—combining evaporation from the soil surface and plant transpiration—reduces moisture content and increases matric suction, contributing to improved slope stability (Tarantino & Dainese, 2021). Under dry conditions, root action resembles a pumping system, extracting water from soil pores and generating pressure gradients that affect the stress state of the material.

The Feddes transpiration reduction model (Figure 1) is one of the most widely used approaches to describe how suction within the root zone controls actual transpiration relative to potential transpiration. This model establishes a threshold suction point (s_3), beyond which transpiration significantly decreases, depending on water availability in the soil and atmospheric demand.

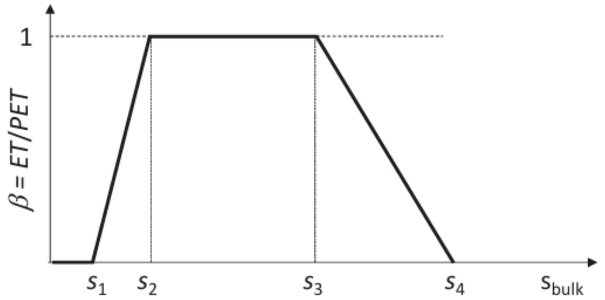

Figure 1. Feddes Reduction Model, Tarantino, 2023.

In the Feddes model (Figure 1), β represents the transpiration reduction factor, ET refers to the actual evapotranspiration rate occurring under soil water limitations, whereas PET refers to the potential evapotranspiration and represents the atmospheric demand for water under non-limiting soil moisture conditions.

Studies by Denmead and Shaw, cited by Tarantino (2023), show that potential transpiration rates vary depending on environmental conditions, and that this variation allows the definition of transpiration reduction curves at different suction levels (Figure 2). This approach is particularly relevant for scaled experimental models like the one in this study, since the amount of vegetation, root depth, and leaf area influence the suction generated in the soil.

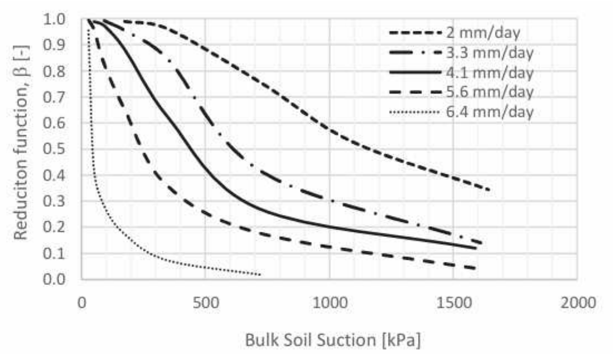

Figure 2. Effect of potential transpiration rate on threshold suction s_3 and on the general reduction curve of maize plants and silty clay soils, Tarantino, 2023.

2.2 Soil- Plant- Atmosphere Continuum (SPAC)

The interaction between vegetation and soil can be represented through the Soil–Plant–Atmosphere Continuum (SPAC) concept (Figure 3), which describes water flow as a series of resistances: soil, root–soil interface, plant vascular system, and leaf surface. This flow is driven by gradients in water potential and depends on both soil hydraulic properties and root architecture.

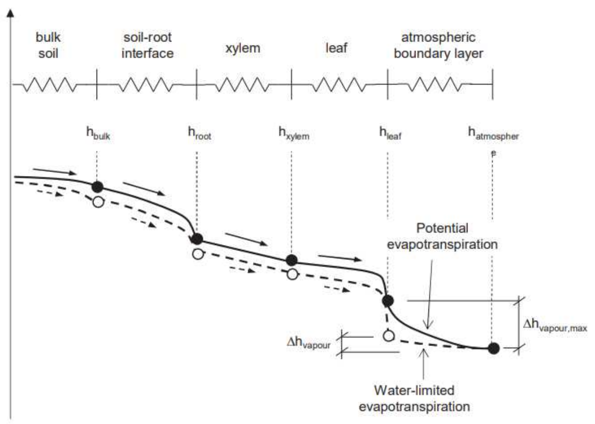

Figure 3. Hydraulic resistances in the SPAC system, Tarantino, 2023.

Factors such as root density and root length strongly influence the system's capacity to maintain suction under dry conditions (Figure 4). A denser root system allows greater water extraction when moisture levels are low, providing a significant hydrological reinforcement effect for slope stability.

In this research, balsa wood was used as an analogue material to simulate the function of tree roots. Its ability to absorb and release water in a controlled manner allows for replication of root-induced suction and moisture redistribution observed in real vegetated systems. The principles described in the Feddes model and the SPAC concept are directly applicable to this experimental setup, where the interaction between the number of trees, root depth, and leaf area determines the hydromechanical behaviour of the soil, particularly in terms of mass loss and moisture reduction.

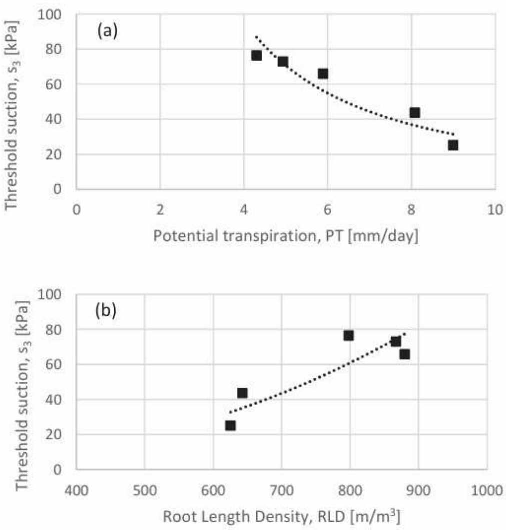

Figure 4. Effect of potential transpiration rate and root length density on threshold suction s_3, Tarantino, 2023.

3 METHODOLOGY

The methodology employed in this research was experimental. The process began with defining the conditions of the base material used in the tests, opting for a fine clayey soil (kaolin) that would allow clear observation of mass variations associated with changes in moisture content and water drainage within the sample.

Subsequently, the material used to simulate vegetation and the variables of interest were defined, considering that balsa wood could reproduce the characteristic suction effect of roots by absorbing surrounding water. To ensure consistency across experiments, both soil type and vegetation analogue were kept constant. At the same time, specific elements such as exposure time, root depth, number of trees, and leaf area were varied. These variations enabled the identification of the configuration that produced the greatest moisture and mass loss at the same wind velocity during testing.

3.1 Preparation of Soil Sample

To prepare the soil sample, completely dry kaolin was used as the base material due to its ability to retain and release water, making it suitable for the experimental conditions. For the tests, the initial sample needed to exhibit a high degree of saturation so that, as water content decreased throughout the experiment, the performance of the setup and the influence of the vegetation analogue on the system could be assessed.

The kaolin was progressively mixed with water to achieve the most homogeneous mixture possible until reaching a moisture content of 31%. Once the desired consistency was obtained, the sample was placed in a container covered with plastic wrap to prevent early moisture loss and was allowed to rest for 24 hours. Afterwards, the soil was sieved through a No. 8 mesh to ensure uniform particle size. The sieved sample was allowed to rest for another 24 hours prior to testing.

3.2 Balsa Wood

Balsa wood was selected as the material to represent vegetation in the experimental model due to its ability to generate suction within the soil. It is hypothesised that balsa wood behaves similarly to natural tree roots. This material can absorb and release water, mimicking the evapotranspiration process that occurs in real vegetation.

Before incorporating it into the model experiments, preliminary suction tests were conducted on the balsa wood. These tests consisted of saturating the samples in a vacuum chamber to ensure full water absorption, followed by a controlled drying process in which exposure times were varied. This procedure made it possible to measure the moisture content and suction capacity of the material.

The results indicate that balsa wood reached a suction of 82.14 MPa and a moisture content of 5.25% after approximately 94 hours of drying.

It was also possible to determine the specific gravity of the balsa wood (0.36 g/cm³) and its void ratio (1.61), confirming a porous structure with high capillary retention. These parameters are essential for understanding the behaviour of balsa wood under conditions similar to natural roots, as they allow quantification of its ability to retain and release water.

Additionally, the water retention curve of balsa wood was developed. This curve is key for describing how the material's water content varies with suction, reflecting its ability to influence the soil moisture regime via evapotranspiration. Figure 5 shows the variation of suction as a function of the degree of saturation (Sr). As moisture content decreases, suction increases nonlinearly, especially at low saturation levels of the high-water retention capacity of balsa wood.

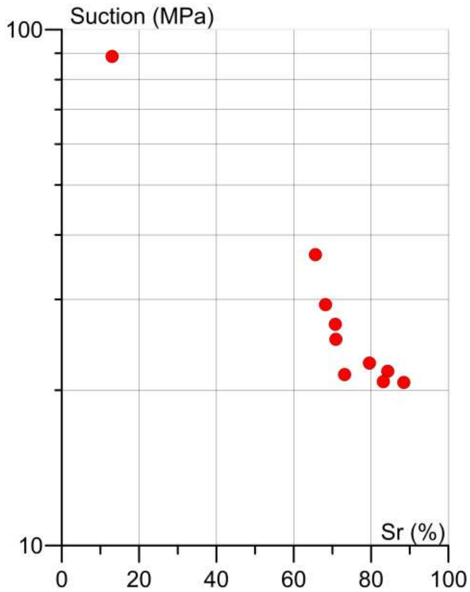

Figure 5. Water retention curve of balsa wood- Suction as a function of degree of saturation.

The results confirmed that balsa wood is an appropriate analogue for simulating root behaviour in scaled models. Its capacity to absorb water and release it gradually effectively reproduces the behaviour of natural roots, contributing to changes in soil moisture content and overall system stability.

The research was conducted in two experimental phases. In Phase 1, the trees were inserted into perforations made in the compacted soil. However, this method generated discontinuities and limited root–soil interaction. For this reason, the tree model was redesigned in Phase 2, unifying the root and canopy in a single balsa structure and integrating it during soil compaction. This modification ensured a more realistic connection between vegetation and the granular medium.

3.3 Preparation of the Mould

Preparation of the sample in the acrylic mould began with a 1.5 cm layer of sand, which provided support and levelling. A filter paper layer was then added to prevent mixing between the sand and the kaolin and to promote uniform drainage throughout the system.

Kaolin was introduced in four successive layers. Each layer was uniformly compacted, and perpendicular grooves were made using an appropriate tool to ensure interconnection between layers and achieve greater homogeneity. At this stage, balsa wood sticks representing tree roots were inserted (see Figure 6).

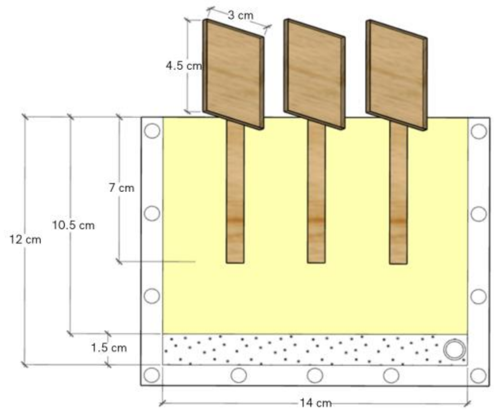

Figure 6. Sample and trees layout for test 1.

Once all kaolin layers were placed, the top of the mould was covered with plastic wrap to prevent moisture loss during the resting period before testing.

3.4 Saturation of the Water Column

After preparing the sample in the acrylic mould, a water column was connected to the system. The valve was opened to purge the mould and remove any trapped air bubbles to ensure uniform saturation.

After purging, the valve was closed, and the system was left undisturbed for five days. During this period, water ascended through the kaolin layers by capillarity, ensuring even distribution and complete saturation. At the end of the saturation period, the soil and balsa wood were visibly fully soaked, ensuring ideal conditions for subsequent experiments.

3.5 Experimental Setup

The experimental setup (Figure 7) was designed to control the interaction between soil, vegetation, and atmosphere. To achieve this, several instruments were used:

- ORIX MF930-BC fan, allowing wind speed adjustment; used to simulate atmospheric wind and induce evapotranspiration.
- Precision scale for measuring mass loss over time.
- Thermocouple for monitoring temperature and relative humidity.
- One wind speed sensor.
- One relative humidity sensor.

- A polystyrene enclosure to create a closed system with uniform airflow, preventing external disturbances during the test.

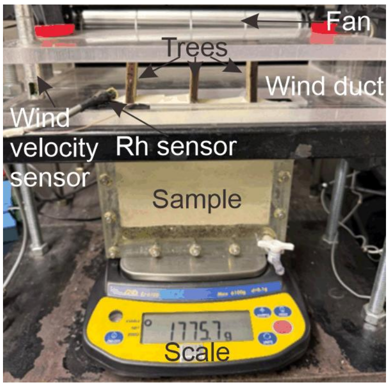

Figure 7. Experimental setup, Caicedo, and. Silva, 2024.

3.6 Variables

The variables considered during the tests were:

- Root depth: 1/3H and 2/3H (3.5 cm and 7 cm).
- Number of trees: 2, 3, and 5 units.
- Leaf area of a unit tree: 27 cm² and 45 cm².
- Exposure time: 3 and 6 days.
- Wind speed: 7 m/s.
- Temperature and relative humidity: stable, with no significant variations.

The experiments were carried out at an average temperature of 18°C, which reflects the normal ambient conditions of the laboratory where the tests were performed. Keeping the temperature stable throughout the experimental period was important to ensure that any changes observed in moisture and suction were primarily related to the vegetation variables, rather than to thermal variations.

3.7 Test procedure

Mass loss was recorded daily using a high-precision balance, while water content was measured at the end of the test at 1 cm depth intervals. For each sampling point, the wet mass of the soil was recorded immediately after the test. Samples were then placed in an oven at 110 °C for 24 hours to determine their dry mass. Moreover, suction measurements were performed using digital tensiometers placed at specific depths.

4 RESULTS

A total of four experimental tests were conducted, whose parameters and specific conditions are summarised in Table 1. This table presents the variables used in each test, as well as the resulting mass loss of the soil samples. As previously mentioned, the parameters that varied among the tests were: root depth, number of trees, leaf area, and exposure time.

With this test set, the goal was to identify the combination of variables that produced the greatest soil mass loss, evaluating the influence of each factor.

Table 1. Variables for each test and results for mass loss.

Test	1	2	3	4
R_d (cm)	7	7	3.5	3.5
N_t	3	3	5	2
F_l (cm^2)	27	45	27	27
t_e (days)	6	6	6	2
W_v (m/s)	7	7	7	7
T °C	18.7	18.6	18.2	18.7
R_h (%)	57.6	54.2	55.4	53.6
m_l (g)	62.6	100.4	60.1	15.8

R_d root depth, N_t number of trees, F_l: foliation area of a unit tree; t_e elapsed time; W_v Wind velocity, T temperature, R_h relative humidity, m_l mass loss.

Figure 8 provides a comparative view of total mass loss for the four tests, along with the slope of each curve, used to evaluate and compare the mass loss rate in each test.

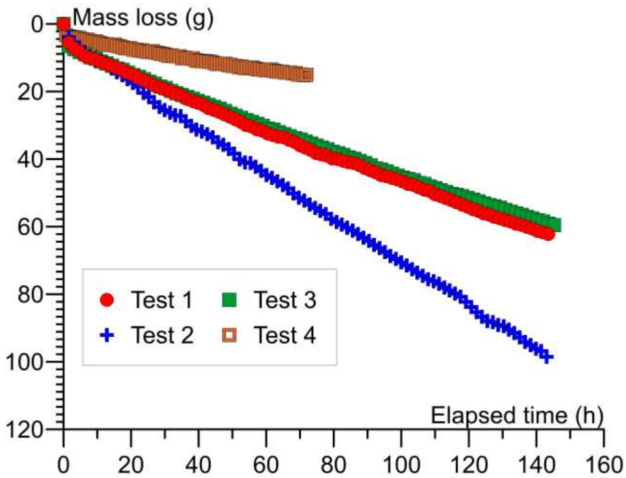

Figure 8. Mass loss curves for all four tests.

Figure 9 illustrates vertical moisture distribution and suction maps for each test. These graphical representations clearly display trends in soil behaviour under the influence of simulated vegetation.

Figure 10 shows the results of the suction measurements obtained using a T5x tensiometer. Measurements were taken up to a maximum depth of 7 cm, determined by the drill bit length used to prepare the insertion holes. Suction was measured directly in the soil (kaolin), at points adjacent to each tree.

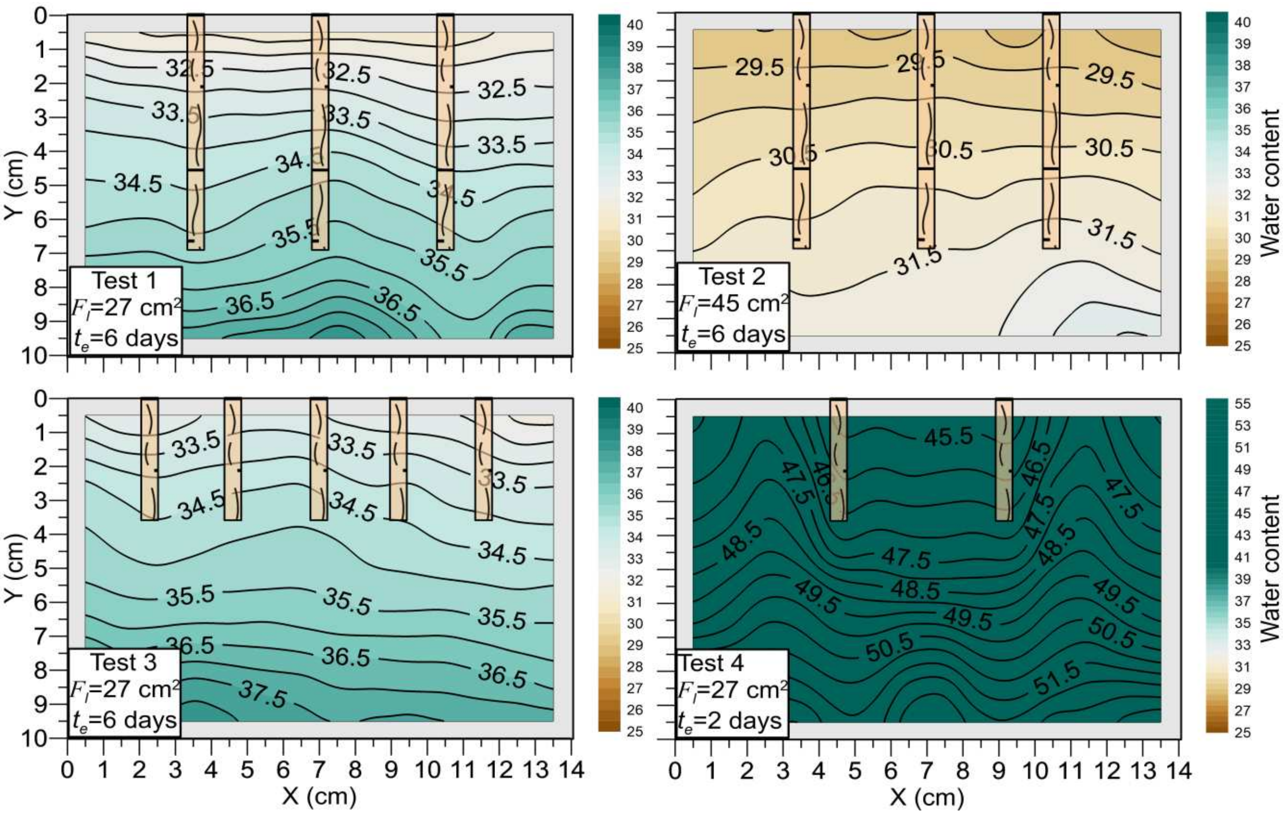

Figure 9. Distribution of water content for tests 1 to 4.

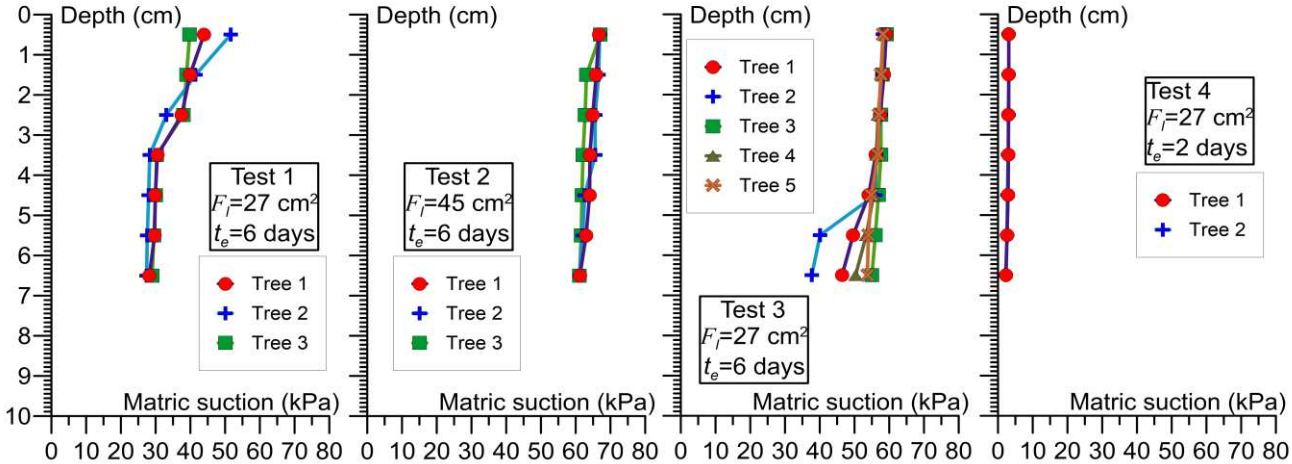

Figure 10. Suction pressure around the trees for tests 1 to 4.

4.1 Mass loss

Figure 8 shows the mass loss achieved on the four tests. In Test 1, three trees were used, with deep roots of 7 cm and a medium leaf area of 27 cm². Under these conditions, a mass loss of 62.6 g was recorded over six days, reflecting a stable suction behaviour. In Test 2, the number of trees and root depth remained the same, but leaf area was increased to 45 cm², which led to a higher evapotranspiration rate and a significantly greater mass loss: 100.4 g. This difference highlights the critical role of leaf area in accelerating soil drying.

In contrast, Test 3 used five trees, increasing vegetation density, but root depth was reduced to 3.5 cm. Despite having more trees, mass loss was 60.1 g, similar to Test 1, which suggests that root depth had a greater influence on moisture extraction than the number of trees.

Finally, Test 4 represents the least effective configuration: with only two trees, shallow roots (3.5

cm), the same leaf area as Test 1, and a shorter exposure time (3 days), the lowest mass loss was recorded: 15.8 g.

Overall, the results demonstrate that several variables influence mass loss in saturated soil. Comparing the curves from all four tests, Test 2 displays the steepest slope and therefore the greatest accumulated mass loss (100.4 g), while Test 4 shows the lowest (15.8 g), with a much lower slope. These contrasting behaviours are directly related to the combination of variables used in each case.

In Test 2, the same root depth as Test 1 was maintained (7 cm), but leaf area increased to 45 cm², enhancing evapotranspiration. These results confirm that not only vegetation density but also root depth, leaf area, and exposure time are determining factors in the hydrological behavior of the soil–vegetation–atmosphere system. The combination used in Test 2 proved the most efficient for inducing suction and mass loss, evidencing the strongest effect of simulated vegetation on soil moisture redistribution.

Figure 8 also allows observing a linear trend of mass loss over time, it allows assessing the mass loss rate (slope), expressed in grams per hour (g/h). As noted, Test 2 presents the highest slope, 0.6571 g/h, indicating a significantly higher mass loss rate relative to the other tests. In contrast, Test 4 shows the lowest slope (0.1649 g/h), reflecting a reduced mass loss rate, likely associated with less favourable conditions such as lower leaf area, shorter exposure time, and shallow roots.

4.2 Moisture

The moisture distribution shown in Figure 9 shows clear differences among the four tests. In Test 1, moisture gradually increases with depth, reaching values up to 41.4% at the base (10 cm), while minimum values of 29.7% appear at the surface. This trend reflects more efficient water extraction in upper layers. In Test 2, the lowest moisture values of all tests were observed, with surface minima of 26.1% and only 34.3% at the bottom. This distribution indicates intense evapotranspiration driven by the larger leaf area, consistent with the high mass loss recorded.

Test 3 shows high moisture retention at deeper layers (40.2%) and lower values at the surface (30.5%). Finally, Test 4, with only two trees and short exposure (3 days), exhibits the highest moisture levels across the entire profile, with maximum values of 55.4% at the bottom and no pronounced drying at the surface.

In all cases, a consistent trend was observed: greater depth corresponds to higher moisture content, indicating that the upper layers dry more quickly. This behaviour is fully consistent with the mass loss data. Test 4, having the lowest mass loss, retained more moisture throughout the soil profile. Conversely, Test 2 displayed considerably lower moisture content, directly linked to its higher mass loss.

4.3 Suction

The suction distribution profiles, shown in Figure 10, reveal a clear inverse relationship with moisture: lower moisture corresponds to higher suction. This pattern is evident in Tests 1, 2, and 3, where suction values are high. Test 2, which showed the greatest mass loss and lowest moisture levels, recorded suction values up to 67.1 kPa. In contrast, Test 4, with minimal mass loss and the highest moisture levels, recorded much lower suction values, with maxima of only 3.1 kPa.

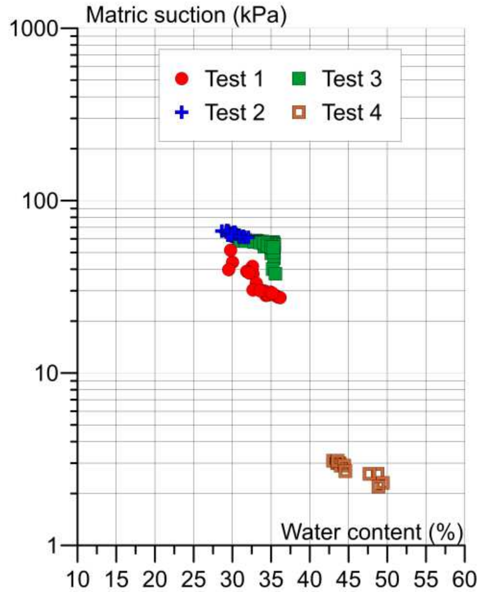

Figure 11. Water retention curve resulting from the measures of water content and suction in different points of the sample.

A vertical trend was also observed: suction decreases with depth, consistent with higher moisture content in deeper layers, reducing the suction required for water extraction. Thus, suction data confirm both the surface drying pattern and the influence of the number of trees, root depth, and leaf area on water redistribution within the soil.

The results indicate that soil behaviour varies with depth and that roots influence not only the region in which they are located, but also a lateral zone of influence capable of extracting water from surrounding soil, even from the edges of the mould. When the number of trees, root depth, leaf area, and exposure time increase, the suction effect intensifies, resulting in greater mass loss and more pronounced reductions in moisture content.

Test 2 produced the most favourable results in terms of mass loss, attributable to its larger leaf area (45 cm²), which enhanced evapotranspiration and suction. Although this research focused on identifying the combination of variables that generated the greatest mass loss in a kaolin sample, the findings also confirm that vegetation is an effective method for slope stabilisation. This technique improves soil performance by increasing shear strength and mitigating destabilising factors through the reduction of water content.

The measures of water content and suction taken around the trees at the end of each test allow assessing the water retention curve of the soil. This WRC is shown in Figure 11, where it is possible to infer the WRC of the soil during drying.

5 CONCLUSIONS

The physical model developed using kaolin and balsa wood trees demonstrated that vegetation has a direct influence on moisture redistribution and soil suction, effectively reproducing the evapotranspiration processes that occur under natural conditions.

The combination of deep roots and large leaf area, as in Test 2, was the most efficient in generating mass loss, reaching 100.4 g in six days, which shows that these variables strongly enhance water extraction in the system.

An inverse relationship between moisture content and suction was observed: the upper soil layers, which dry more quickly due to wind and vegetation effects, exhibited higher suction values compared to deeper layers.

Root depth had a greater influence on moisture reduction than the number of trees. Test 1, with three trees and 7 cm roots, produced greater mass loss than Test 3, which had five trees but 3.5 cm roots.

The moisture profile showed a consistent trend: greater depth corresponded to higher water content, confirming that vegetation-induced drying primarily affects the upper layers. The suction maps clearly demonstrated that the influence of roots extends beyond the immediate area where they are installed, producing a lateral zone of influence capable of extracting water even from the edges of the soil column.

Balsa wood proved to be a reliable analogue material for representing root behaviour, due to its ability to gradually absorb and release water, which was essential for reproducing root-induced suction phenomena.

The results of this study confirm that vegetation is a non-invasive and effective strategy for improving slope stability, as it reduces soil water content and increases suction, thereby enhancing shear strength.

Although this study focused on evaluating different vegetation configurations, a reference test without trees was not included in this experimental study. Incorporating a baseline case without vegetation would allow for a more direct quantification of the net effect of the simulated trees on moisture reduction and suction development.

It is recommended that future studies incorporate the use of a geotechnical centrifuge to reproduce full-scale field conditions, allowing a more precise analysis of vegetation effects under inertial forces equivalent to real loading conditions. This advanced experimental approach would enable more robust validation of the results obtained in the laboratory. Additionally, expanding the range of vegetation variables—such as root density, types of foliage, and longer exposure periods—is recommended to optimise the design of the experimental model.

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